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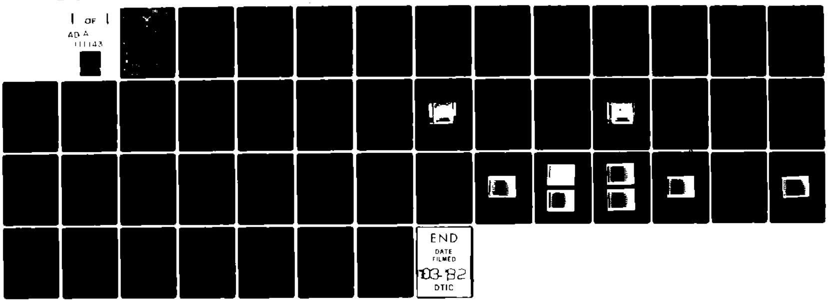

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STARTING TRANSIENTS IN SUPERSONIC NOZZLES AND NOZZLE-DIFFUSER ASSEMBLIES

THESIS

AFIT/GA/AA/81D-6 — Thomas Gregory Gates, 2Lt, USAF

AFIT/GA/AA/81D-6

STARTING TRANSIENTS IN SUPERSONIC NOZZLES AND NOZZLE-DIFFUSER ASSEMBLIES

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

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Master of Science

by

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Graduate Astronautical Engineering

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Approved for public release; distribution unlimited.

Preface

Many people are responsible for the completion of this investigation and the quality of the learning experience it represents. In particular, I would like to thank my advisor, Dr. William C. Elrod, without whom this thesis would not have been possible. I would also like to thank my Advisory Committee, Dr. Wright and Dr. Hitchcock, for the help and guidance they provided throughout the study. I especially like to acknowledge the help provided by technicians Mr. William V. Baker and Mr. H. Leroy Cannon without whom I would still be attempting to cause my equipment to function properly. I would also like to thank everyone at the AFIT Model Shops, especially Mr. Carl Shortt and Mr. John Brohas, for their help in fabrication of the necessary equipment for this work.

Finally, I would like to thank my wife, Stella, for the patience and guidance she provided for me throughout my entire investigation.

2Lt Thomas Gregory Gates

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H_t ≡ Throat Height

$\bar{M}_{S1}$ ≡ Average Test Section Entrance Mach Number

P_1 ≡ Shock Tube Driven Section Pressure Inches of Mercury

P_4 ≡ Shock Tube Driver Section Pressure Inches of Mercury

$\bar{P}_{41}$ ≡ Average Diaphragm Pressure Ratio

t ≡ Time, Seconds

x ≡ Distance, Feet

Abstract

In this investigation, the flow processes involved in shock induced starting of nozzles and diffusers similar to those used in gasdynamic lasers were studied. Two geometrically similar nozzles were used. The throat opening in the large single nozzle was 0.276 inches. The other was an array of nine nozzle-passages in which the throat opening was 0.069 inches. Downstream of the nine nozzles were nine diffusers whose minimum opening was 0.286 inches. These 2-dimensional nozzles and diffusers were 0.75 in. thick. The multiple nozzle and diffuser array is similar to those used in gasdynamic lasers. Schlieren photographs of the flow in these channels were the primary source of data for this investigation.

A fully started condition of uniform supersonic flow was achieved throughout the entire test area for both test sections. The processes leading to this condition were highly dynamic and complicated. It was found that successful starting depended not only on the initial diaphragm pressure ratio, but also the downstream test cell configuration. Starting the large single nozzle was enhanced by an increase of flow channel just downstream from the nozzle. This decreased the strength of the incident shock wave and thereby increased the pressure ratio applied across the nozzle. As a result, the gasdynamic starting shock could pass on out of the nozzle at lower shock tube diaphragm pressure ratios than would have been the case if the area had remained constant in the flow channel behind the nozzle. The starting of the nozzle-diffuser array appears to depend on the flow area geometry in a non-linear manner.

STARTING TRANSIENTS IN SUPERSONIC NOZZLES AND NOZZLE-DIFFUSER ASSEMBLIES

I. Introduction

Background

This study deals with the start-up processes in supersonic nozzles and diffusers similar to those used for gasdynamic lasers (GDL). A GDL uses the high energy, low temperature molecules that are generated in the flowing media for the lasting action. Two-dimensional convergent-divergent supersonic nozzles are normally used in a linear array just prior to the cavity in which the lasing is to take place. The laser output emerges in a direction perpendicular to the flow direction.

As a result of the need for greater beam power and increased operating efficiency, GDL and the processes leading to the lasing have been the subject of in-depth investigations. One such investigation was done by Weber (Ref 1) at the Air Force Institute of Technology (AFIT). This project is a continuation of the work he started using Mach 3.2, 2-dimensional, convergent-divergent supersonic nozzles. This study explores the conditions which lead to uniform supersonic flow in the cavity downstream of the nozzles and in the diffuser passages.

Shapiro (Ref 2), Leipmann and Roshko (Ref 3), and many others describe the "steady state" supersonic nozzle starting process. This occurs by increasing the inlet pressure and/or decreasing the exit pressure to get uniformly subsonic flow in the nozzle. Continuing to increase the pressure differential across the nozzle results in sonic conditions at the throat and the formation of a normal shock that is moved downstream until it exits the nozzle. Flow in the entire nozzle is essentially uniform at any time; therefore, the process may be considered steady state. Allowing the pressure ratio to remain constant from inlet to exit at any time results in flow within the nozzle existing in the form dictated by the pressure ratio.

For this study the shock tube will be used to initiate the flow within the nozzle and diffuser passages instead of the quasi-steady state start-up described above. This process is initiated by a moving shock wave traveling into the flow passages in which the fluid is stationary. As the incident shock wave travels into the test section, part of the wave is reflected off the nozzle inlet. The pressure and temperature behind the reflected shock wave are much higher than behind the incident shock wave. The conditions behind the reflected shock are used as the upstream chamber condition for this study. Behind the incident shock wave, flow begins in the passages to yield sonic conditions at the throat. Given a sufficient pressure ratio the normal shock wave formed at the throat is expelled downstream to the position dictated by the nozzle pressure ratio. This is a simplified description of the use of a shock tube to start the flow in a convergent-divergent nozzle. More detail will be given as related to this investigation.

Objective

The purpose of this study is to investigate the transient start-up processes that occur in supersonic nozzles and diffusers similar to those used in GDLs. These highly dynamic processes will be observed photographically for two different test assemblies. This investigation will concentrate on the processes that occur prior to and leading to a fully started condition in both assemblies. One test section consists of a single large nozzle while the other is an array of nine nozzle and diffuser passages.

Methodology

The test facility for this study is the AFIT/ENY 4 in. by 8 in. by 20 foot shock tube. The primary data collected is a schlieren photograph of the flow in each of the two test sections. In this investigation ambient temperature air is used as the working fluid throughout the shock tube. Classical methods of shock tube performance analyzation by Leipmann and Roshko are used.

The shock tube is operated with each test run producing a single photograph. From this photograph and its associated pressure ratios and timing data, the values of the flow quantities that exist during the initiation of flow can be determined. The shock tube pressure ratio range that is used in this study is 5.11-95.09. The test section entrance Mach number range associated with these ratios is 1.57-2.55.

II. Apparatus

Shock Tube

This investigation was conducted using the AFIT 4 inch by 8 inch by 20 foot shock tube described by Egan and Foster (Ref 4). The schematic diagram of the shock tube, with its instruments and controls is shown in Figure 1. There are two support systems for operating the shock tube. One is the high pressure driver end pressurization and measurement equipment and the other is the vacuum system for the driven end. All gages and manometers have shut-off valves to prevent damage from the shock wave. On the downstream end of the driven section attached to the exit of the test section is a cylindrical dump tank with approximately 33.5 cubic foot capacity. Vacuum pumps attached to the driven assembly allow the pressure to be reduced below ambient to extend the pressure ratio attainable for experimental work. The driven end pressure was measured using a mercury manometer.

A mylar diaphragm isolates the downstream driven section from the driver end. The diaphragm is ruptured after evacuation of the driven end and/or pressurization of the driver end. The shock strength is determined by the pressure ratio across the diaphragm.

Several processes occur after the diaphragm is ruptured. Into the driver end, a series of rarefaction or expansion waves propagate. These cause a lowering of the temperature of the gas behind them. At the same time a shock wave travels downstream into the driven section. This results in two changes in the driven end fluid. A region of uniform flow is developed which lasts several milliseconds. The shock wave also raises the temperature and pressure of the fluid. See Figure 2 for the x-t diagram of these waves. Since there is a temperature difference

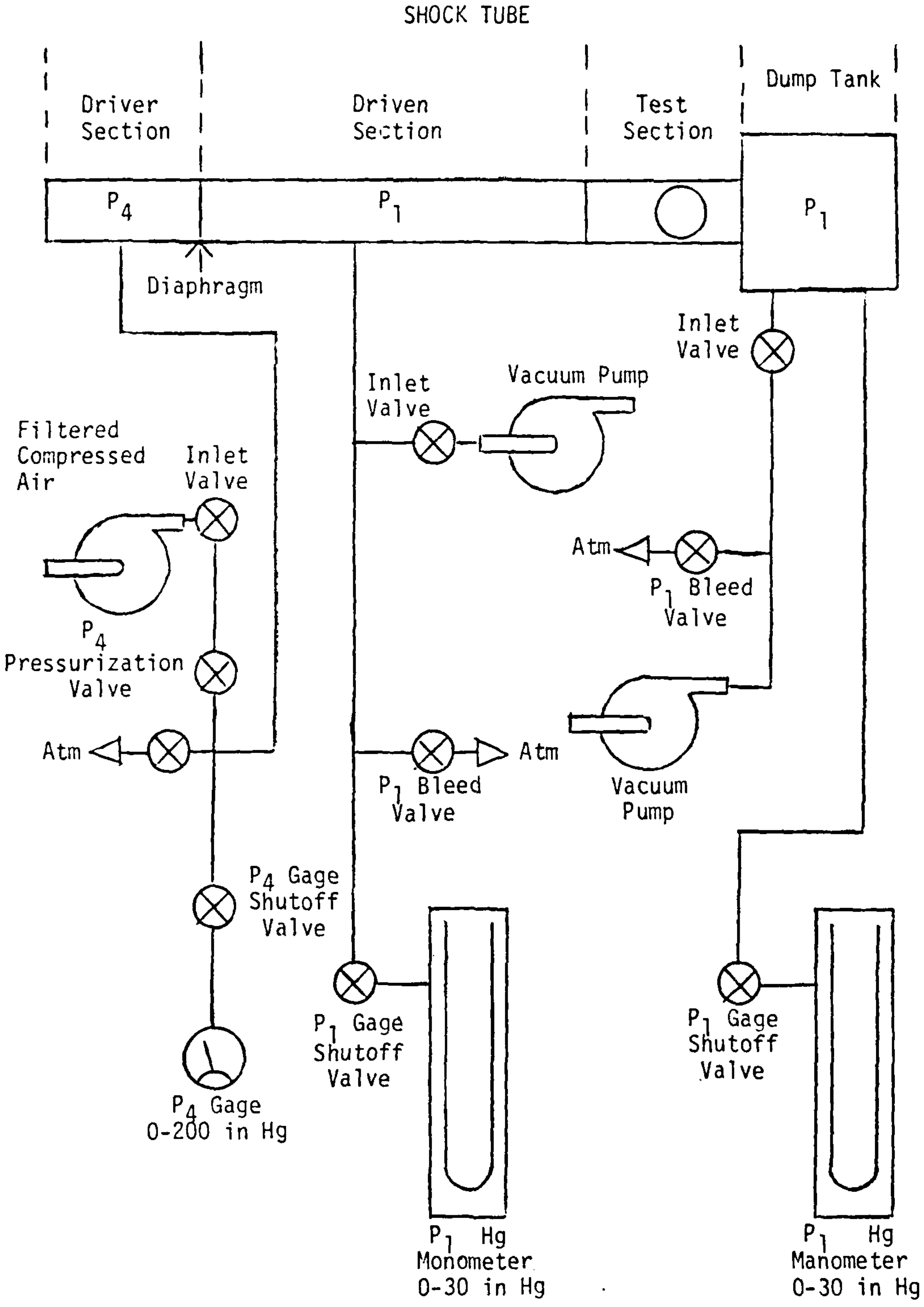


Fig 1. Shock Tube System

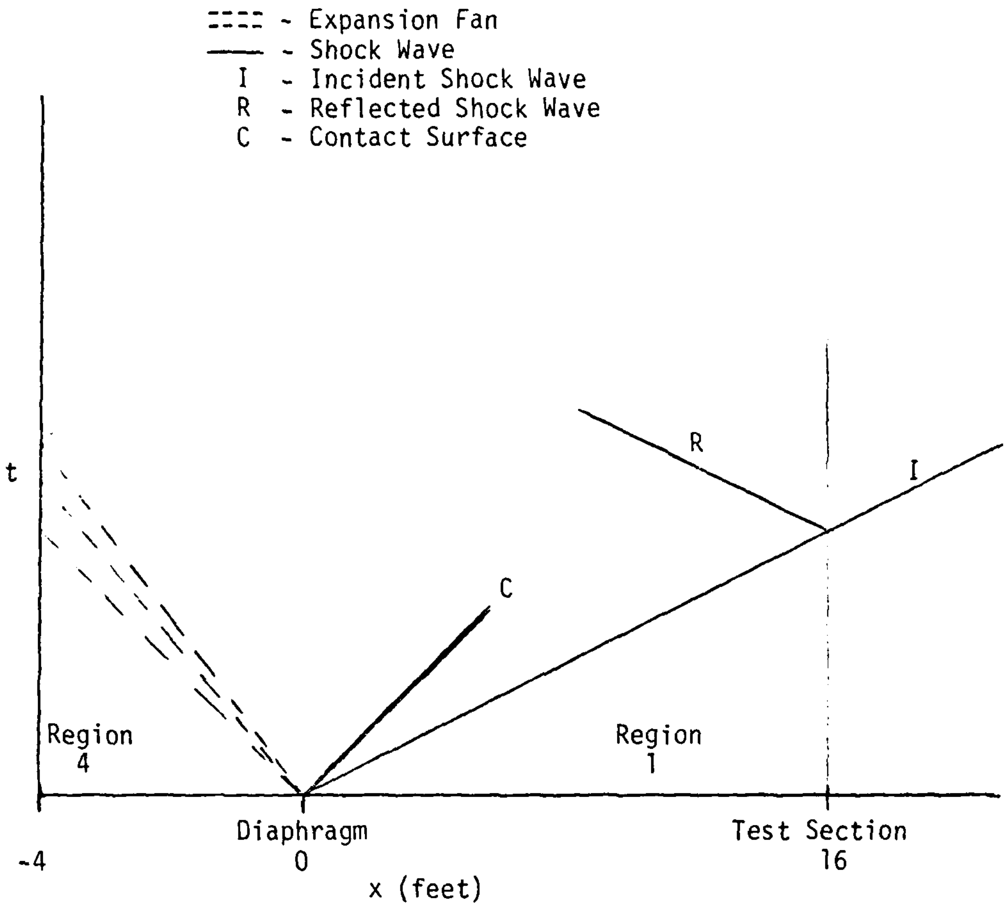


Fig 2. Shock Tube Flow Patterns

between the two sections, a contact surface of temperature discontinuity propagates down the tube.

The driver section consists of a four-foot-long aluminum housing that is mounted on a longitudinal and lateral slide arrangement. This allows the end to be moved in order that the pieces of mylar diaphragm could be removed from the driven end and a new diaphragm installed. It is held to the driven section by a hydraulic cylinder actuated lock. Mounted in the driver end is a pneumatic plunger with a sharpened pyramidal tip. This is used to rupture the mylar diaphragm when the desired test conditions are reached. The pressure in this section is measured using a Bourdon tube type gage that is calibrated from 0 to 2υ. inches of mercury (gage). The air supply for pressurization is filtered compressed laboratory air. Air is also the working fluid in the driven section.

The diaphragms between the driver end and the driven end are type A mylar sheets 6.5 in. by 11.5 in. of varying thicknesses. This study uses diaphragms whose thicknesses range from .003 in. to .014 in. Various combinations of the number of sheets and different thicknesses are used commensurate with the pressure ratio range of interest in the investigation.

In order to strengthen the shock entering test section, an area reduction is used. The increase in strength that results is consistent Withams Rule for area reductions (Ref 5). The 4 in. by 8 in. shock tube dimensions are reduced to 1 in. by 4.5 in. at the sudden contraction point 12 feet from the diaphragm location in the driven end. This provides a four-foot-long section of 1 in. by 4.5 in. rectangular cross-section so that the shock can stabilize after the area reduction.

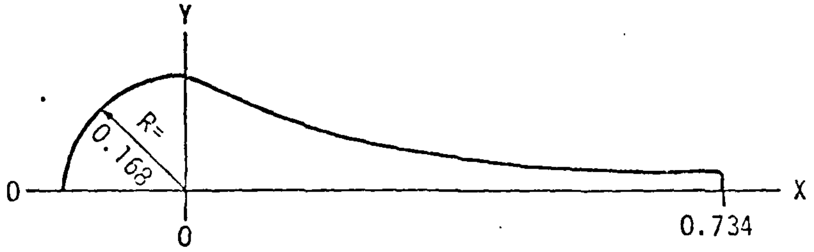
The test sections are connected to the driven end by suitable adapter plates. Toggle bolts allow the test section and dump tank to be detached from the driven end. The exit side of the test sections are attached to the cylindrical dump tank which is mounted on a wheeled platform.

Test Sections

Two test sections are used to complete this study. The first consists of a large single nozzle passage. The second test section consists of a linear array of nine small nozzle passages and nine diffuser passages separated by a single constant area passage. Both nozzles are two-dimensional, convergent-divergent Mach 3.2 supersonic nozzles. The large nozzle has dimensions of four times the respective dimensions of the small nozzle. See Figure 3 for the nozzle sidewall dimensions. Both test sections have windows transparent to visible light in the direction perpendicular to the flow through which the flow could be viewed.

The large single nozzle passage is formed from two aluminum plates whose dimensions are given in Figure 4. These plates are mounted in an aluminum housing which bolts to the dump tank. The windows in this test section are flat circular plates made of optical glass. Figure 5 shows this test section completely assembled.

The second test section is built from eight complete nozzle blades and two half-blades to form nine complete passages. The nine diffuser passages are formed from a similar arrangement of eight diffuser vanes and two half-vanes. A constant area section is located between the nozzle exit and diffuser entrance. The flow from the separate channels is reunited in this section. The nozzle blades are fabricated from plexiglass while the diffuser vanes are constructed of aluminum. The viewing windows



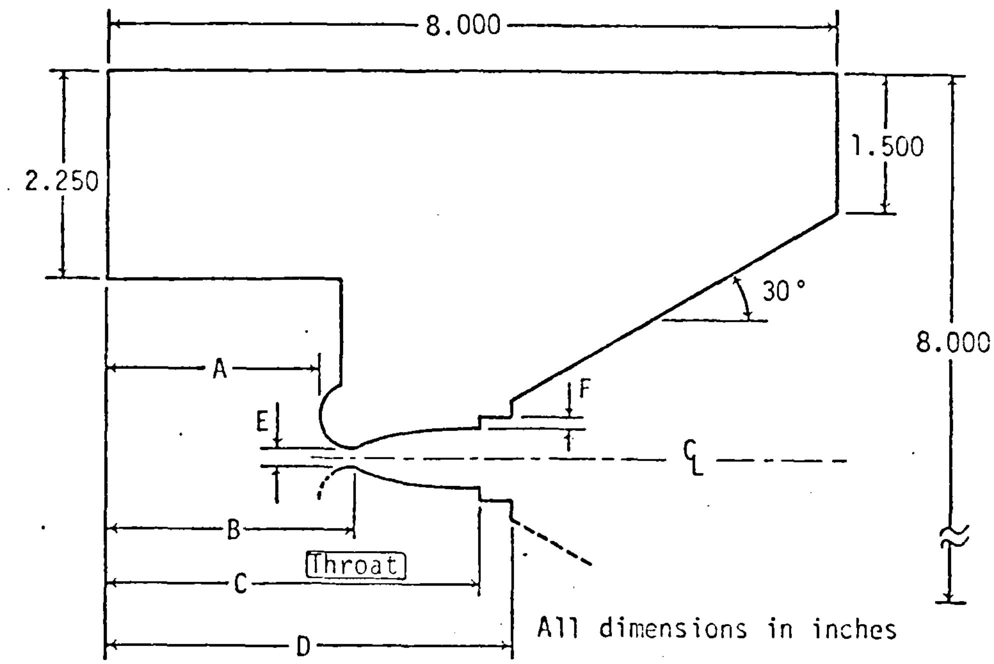
All Dimensions in Inches

X	Y	X	Y	X	Y	X	Y
0.0	0.168	0.133	0.106	0.250	0.071	0.446	0.037
0.044	0.146	0.146	0.101	0.272	0.066	0.485	0.033
0.069	0.132	0.161	0.096	0.295	0.061	0.526	0.030
0.083	0.127	0.176	0.091	0.321	0.056	0.572	0.026
0.095	0.121	0.193	0.086	0.349	0.051	0.621	0.024
0.107	0.116	0.210	0.081	0.378	0.046	0.675	0.022
0.120	0.111	0.229	0.076	0.411	0.042	0.734	0.021

Throat Opening = 0.069 inch
Total Length = 0.902 inch
Design Mach = 3.23

Large Single Nozzle is 4 times all dimensions.

Fig 3. Small Single Nozzle Profile



Material : 0.750 Thick Aluminum

Dimension	Large Nozzle Test Section
A	1.678
B	2.350
C	5.286
D	6.070
E	0.276
F	0.084
Throat To. Sensor B	9.5

Fig 4. Single Nozzle Test Section Dimensions

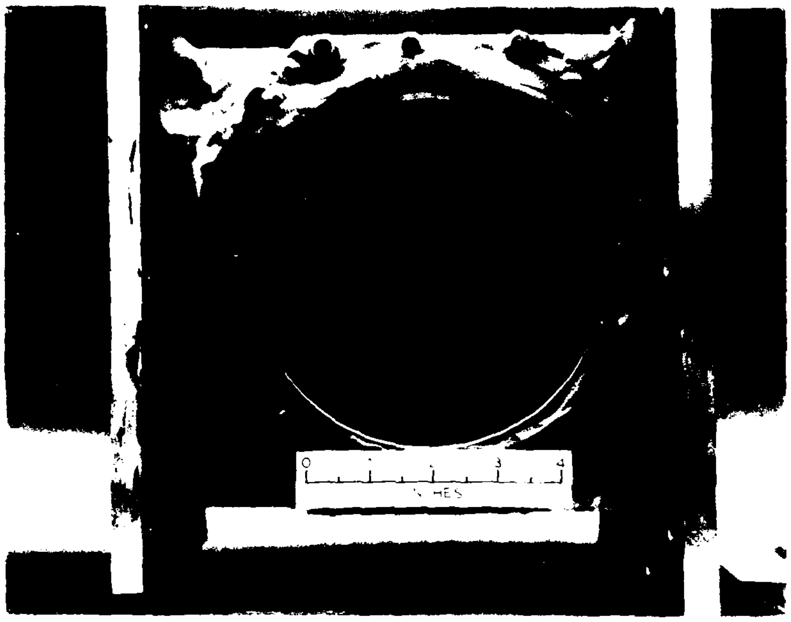


Fig 5. Photograph of Large Nozzle Assembly

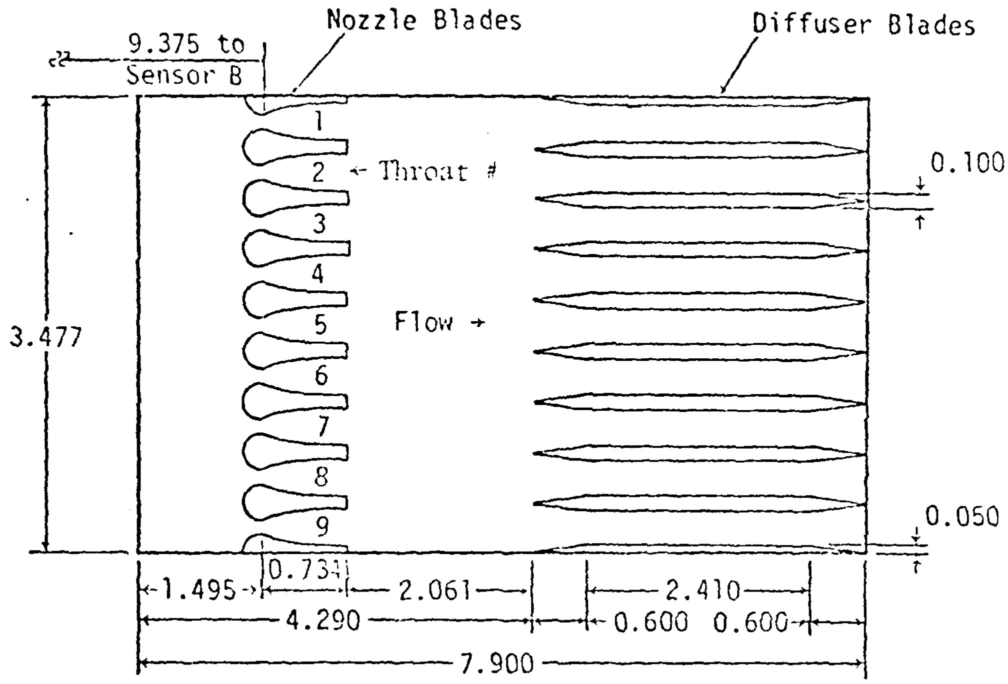
in this section are rectangular in shape and formed from plexiglass. Plexiglass is used instead of optical glass because holes had to be drilled in the windows to mount the blades and vanes. See figure 6 for a layout and dimensions of this assembly. An aluminum shell is used to house the apparatus. This in turn is bolted to the dump tank. Figure 7 is a photograph of this test section.

Optical and Electronic Apparatus

Flow Visualization. The flow data is collected using a single pass schlieren optical system. This data consists of a photograph of the conditions in the test section. From these pictures, the shocks' position, along with other gasdynamic effects, can be determined. Combining this data with the time intervals and pressure ratios measured allows calculation of the shock speed.

The optical equipment consists of two parabolic mirrors, an adjustable knife edge, a lensless camera and a spark lamp. The equipment is arranged as shown in Figure 8. The camera is operated in the always open shutter position. The film is exposed by the light from a spark lamp which has a flash duration of less than 1.0 μsec. The method used in aligning the schlieren camera is detailed in Ref 1, Appendix F.

Electronic Equipment. The purpose of the electronic assembly used in the investigation is twofold. One requirement of the equipment is to trigger the spark lamp at the desired time in order to produce a photograph of the flow field. The other duty is to record two time intervals associated with the flow timings. One time interval is used to calculate the speed of the incident shock wave entering the test section. The second time interval is used in determining the location of the incident



All dimensions in inches (Not to scale)

Material: Nozzle Blades - 0.750 Thick Plexiglas
Diffusers - 0.750 Thick Aluminum

Fig 6. Multiple Nozzle Test Section
(Internal Dimensions Only)

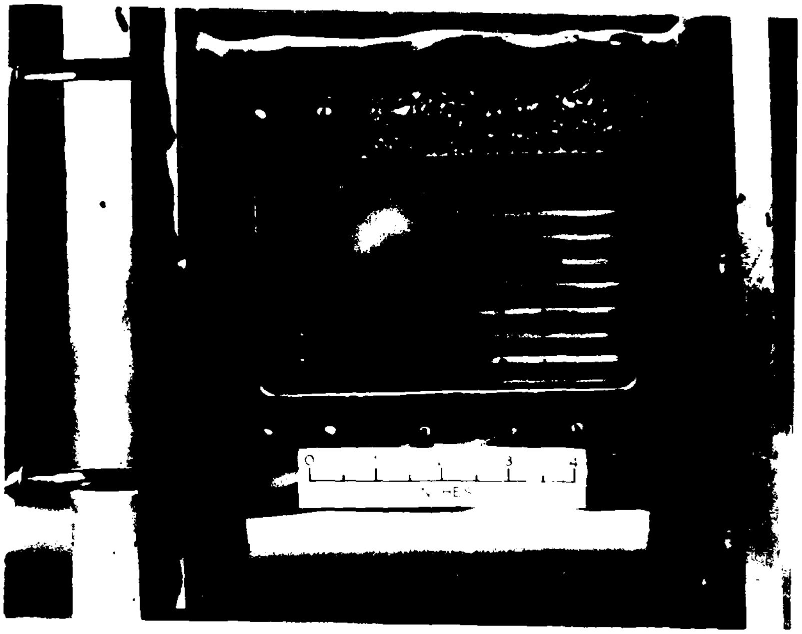
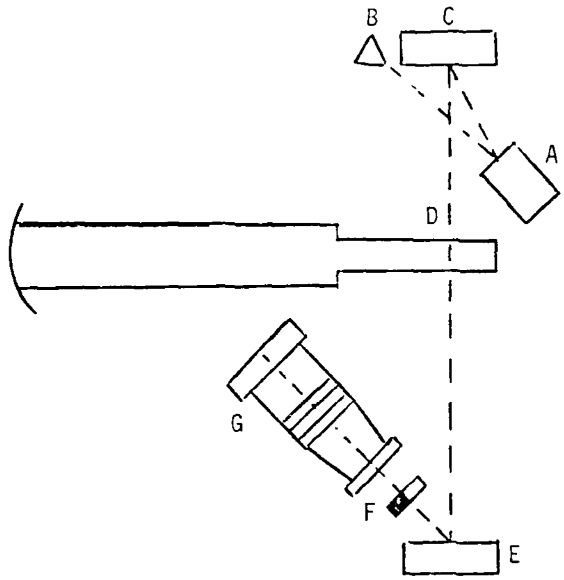


Fig 7. Photograph of Multiple Nozzle Assembly



A - Spark Lamp
B - Photodiode
C - Parabolic Mirror
D - Test Section
E - Parabolic Mirror
F - Knife Edge
G - Camera
--- - Optical Path

Fig 8. Schlieren Optical System

and normal starting shocks relative to the throat of the nozzle. A schematic of the electronic apparatus is shown in Figure 9.

Initiation of the electronic arrays functioning is accomplished by two pressure transducers (sensor A and sensor B). Sensor A is located 2.0 in. upstream of sensor B, while both sensors are connected through instrumentation amplifiers to a dual trace storage oscilloscope. Knowing the distance between the sensors and measuring the time interval associated with the spacing of the signal traces on the oscilloscope allows the shock speed at the entrance to the test section to be calculated.

Sensor B is also used to trigger a BNC delay gate generator. This device outputs a signal, after a preset time delay, which allows the shock wave to be staged through the test section. This output is fed through a silicon controlled rectifier high voltage triggering circuit (see Ref 1, Appendix D). This circuit triggered the cook electric, model 596-4116, spark gap lamp to provide the light flash used for flow visualization.

An unbiased silicon photodiode is located in the field of view of the lamp flash. The output of the photodiode is connected, through an instrumentation amplifier, to a counter. The counter measured the time interval between the events of sensor B triggering and the lamp flash. Knowing this time interval and the location of sensor B relative to the test section, position versus time information could be extracted from the schlieren photographs.

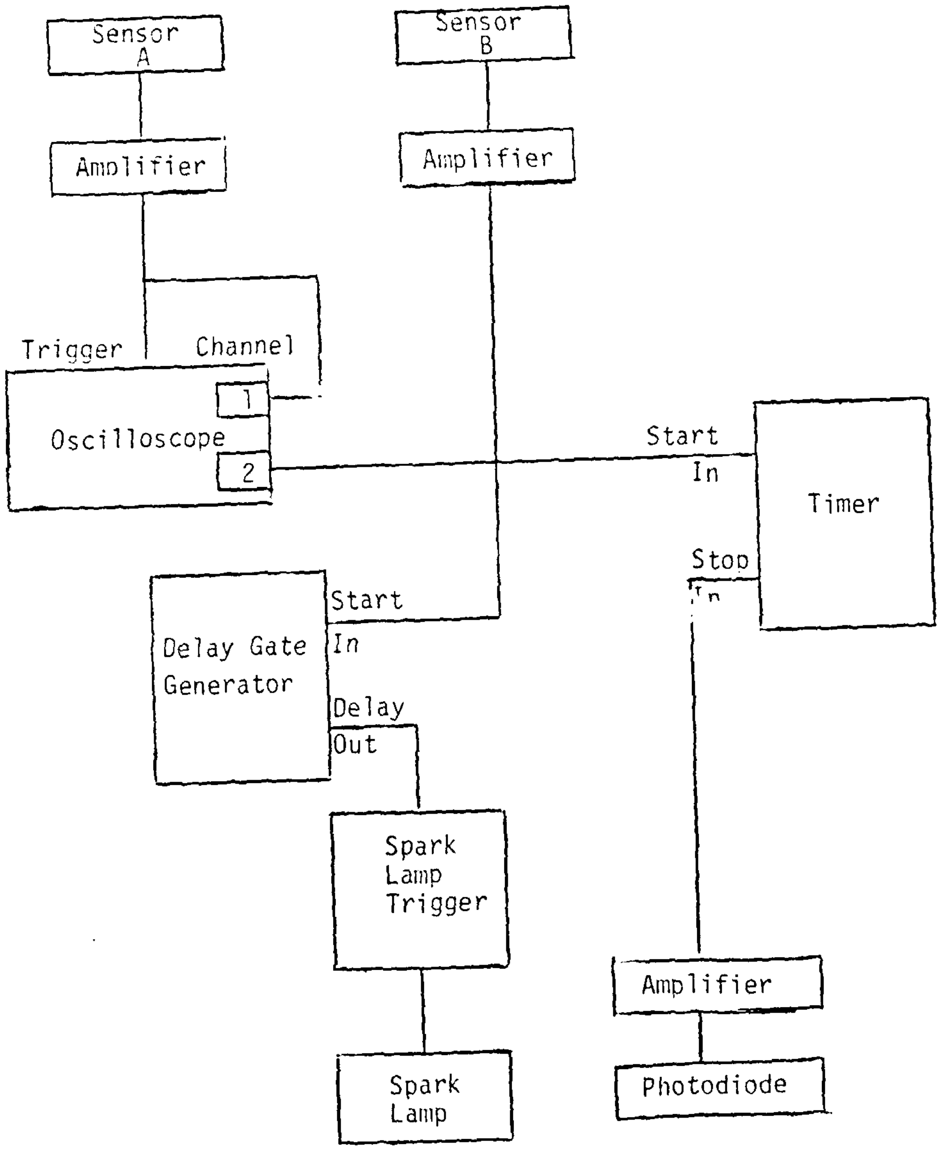


Fig 9. Schematic of Electronic Equipment

III. Results

The data for this investigation consists of schlieren photographs, along with their associated pressures and time intervals. One picture is taken for each shock tube test. The data is divided into 13 series (A through M), each of which has a different pressure ratio or test section. Four series have the large single nozzle as the test section being investigated. Table I summarizes the major differences of each test series.

Large Single Nozzle

In previous work using the large single nozzle, Weber was unable to reach conditions that would allow the nozzle to start. This work deals with the conditions necessary for starting of the large nozzle and the flow processes that occur during start-up. The data will also be compared with Weber's results of the start-up processes in the small single nozzle. Figures 10, 11, and 12 are plots of the time elapsed since the incident shock passed the throat versus location of incident shock and nozzle gasdynamic starting shock for series D, K, and J. Figure 16, Ref 1, shows a similar plot for a similar small single nozzle.

Although Weber conducted several tests at pressure ratios that were higher than the pressure ratios that resulted in fully started nozzles in this study, the large single nozzle never fully started. In the present study in series J and K, the nozzle is fully started. The indicators that lead to this conclusion are the facts that the normal shock is located beyond the exit plane of the nozzle and the presence of mach lines originating from the walls. The major difference in these

TABLE I

Test Summary

Series	Test Section	No. of Tests	$\bar{M}_{S1}$	$\bar{P}_{41}$
A	MN	10	1.57	5.11
B	MN	13	1.67	6.48
C	MN	15	2.25	26.65
D	LSN	23	1.61	7.85
E	LSN	6	-	27.95
F	MN	10	1.85	12.53
G	MN	16	2.18	34.87
H	MN	6	2.13	33.20
I	MN	9	2.17	31.53
J	LSN	13	2.46	65.38
K	LSN	16	2.14	29.06
L	MN	12	2.55	95.09
M	MN	10	2.37	65.38

where:

Test Section Designations are: LSN $\equiv$ Large Single Nozzle; MN $\equiv$ Multiple Nozzle and Diffuser Array

$\bar{P}_{41}$ $\equiv$ Average Diaphragm Pressure Ratio

$\bar{M}_{S1}$ $\equiv$ Average Test Section Entrance Mach Number tests is that the large dump tank was attached to the test section in this study; whereas, in the previous study the channel was blanked off just aft of the nozzle. It is believed that the large cross-section increase beginning at the nozzle exit and extending into the tank allows for pressure relief to propagate back into the nozzle after the incident shock has passed into the tank in this study. In the previous study without the dump tank, the incident shock could reflect back into the nozzle and negate any possibility of pressure relief from the expansion wave just mentioned.

In series D the pressure ratios is insufficient to fully start the nozzle even after pressure relief has occurred (See Figure 10). This can be seen by the fact that the normal starting shock only moves out to a location of 4.5 Throat Heights (H_t), and this is still located within the nozzle. (The nozzle exit plane is located at 11.5 H_t). At 3.8 H_t, there appears to be a temporary pause by the normal starting shock while it waits for a pressure adjustment from the incident shock entering the tank. After the pressure adjustment occurs in test series D, the normal starting shock then moves out to 4.5 H_t and stops there as dictated by the enhanced nozzle pressure ratio.

Both series J and K yield fully started nozzles. Series K (Figure 11) has a lower diaphragm pressure ratio than series J. There is a definite pause in the movement of the normal shock toward the exit at 8.8 H_t in series K. Since there is a static pressure increase across the incident shock, the pressure ratio the nozzle sees is less than the full pressure ratio from the nozzle chamber to the undisturbed fluid ahead of the incident shock wave. Therefore, the gasdynamic starting shock stops at the location dictated by the higher nozzle back pressure. A possible

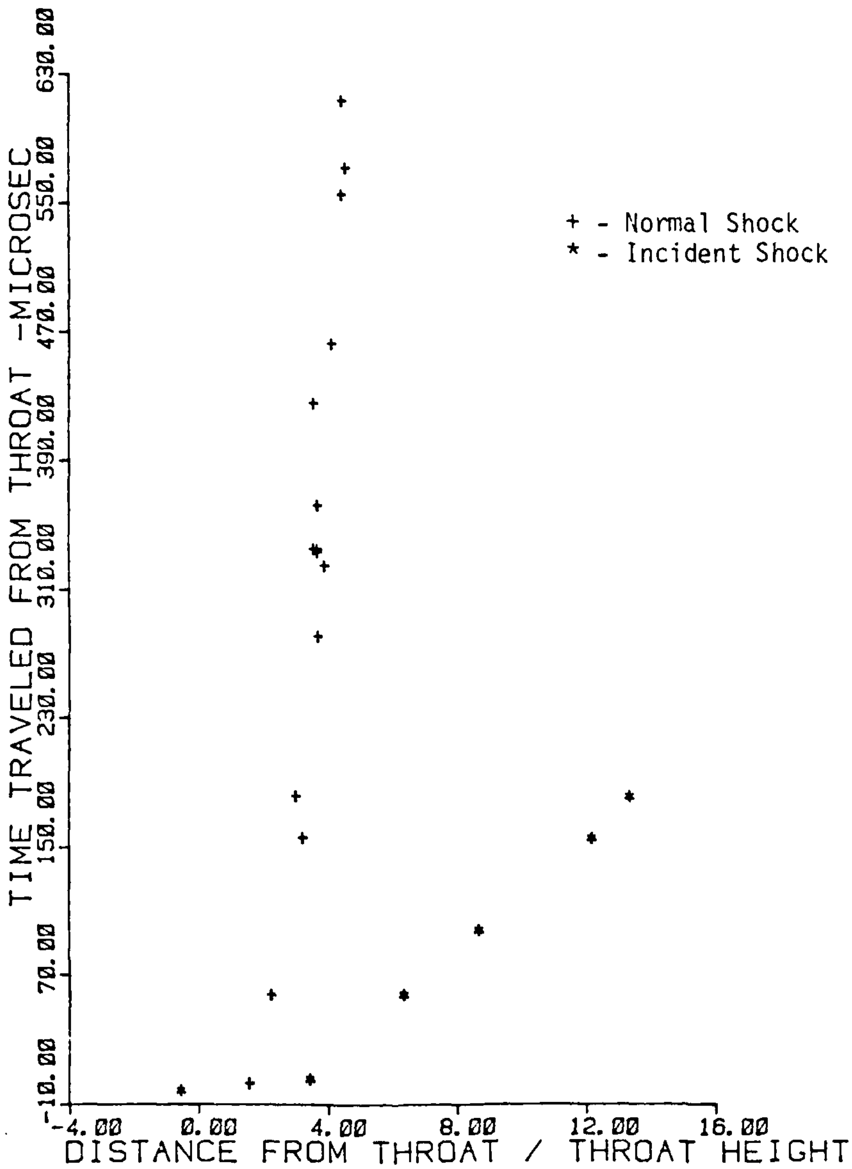


Fig 10. Shock Position in LSN for Series D

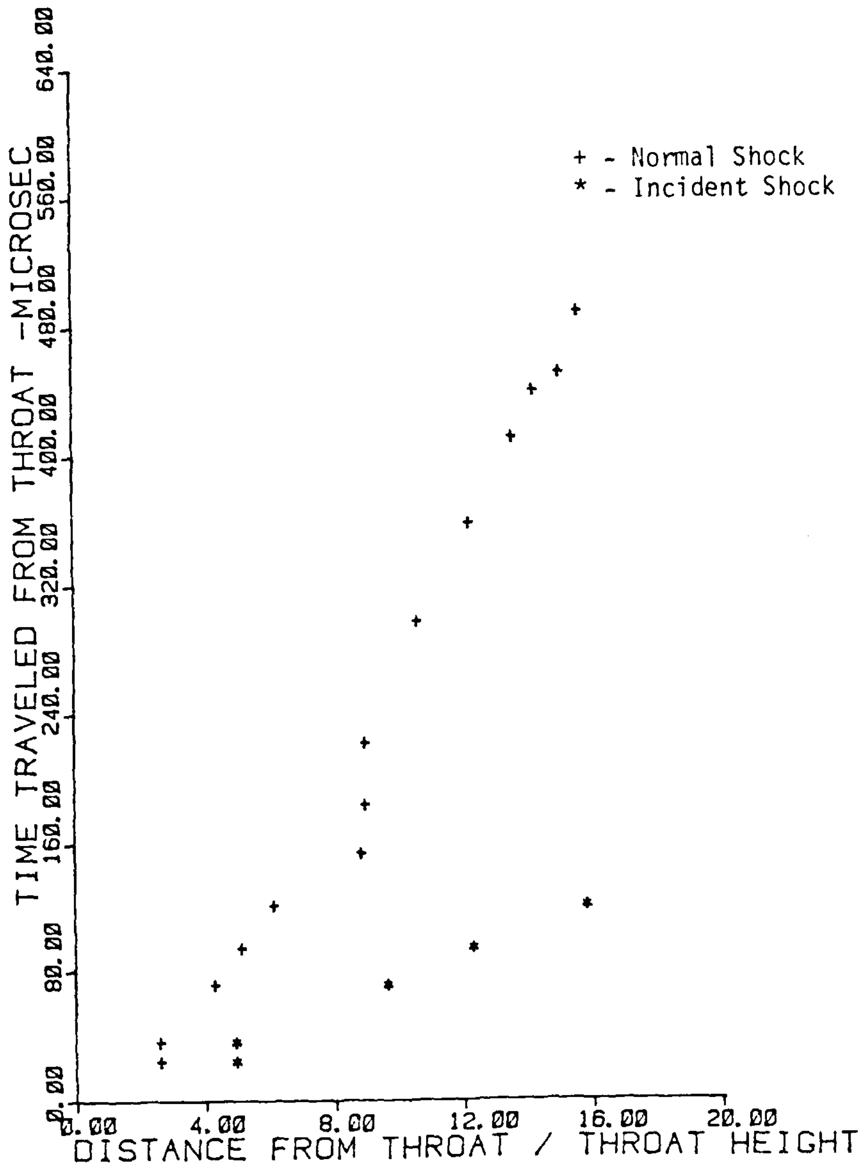


Fig 11. Shock Position in LSN for Series K

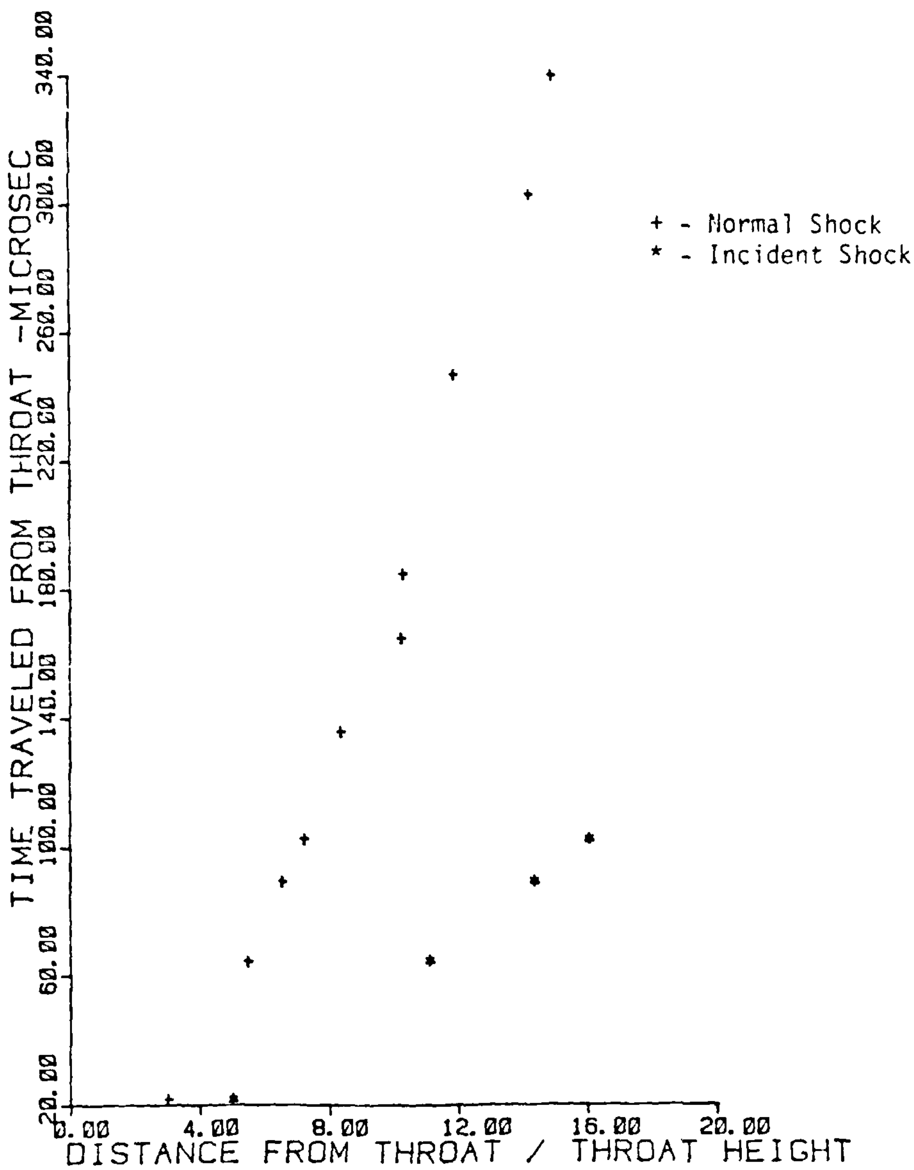


Fig 12. Shock Position in LSN for Series J

mechanism for the pressure relief is that after the incident shock is reduced in strength by expanding into the greatly enlarged section, a series of expansion waves propagate into the nozzle to relieve the exit pressure and allow the nozzle starting shock to be expelled from the nozzle. Weber's work with the small single nozzle also indicated this trend. It is believed that the reason pressure relief occurs in that assembly to a minor extent is that since the nozzle is smaller there is a sufficient increase in the cross-section of the test section to allow some pressure relief before the reflected incident shock wipes out the pressure decrease.

As seen in Figure 12, there is no definite pause in series J. It is believed that due to the high initial pressure ratio across the nozzle there is still a sufficient pressure ratio left to fully start the nozzle, even after the pressure increase across the incident shock. It can be seen that the phenomenon that occurs during shock induced starting of the nozzle is a function of the pressure ratio across the diaphragm and the downstream configuration of the flow passage. In some cases in which the applied pressure ratio is relatively low, as in series K, an increase in flow channel area behind the nozzle makes possible fully starting the nozzle. In Weber's work the exit of the test section was just closed off while in the present study the incident shock expanded into a dump tank. This allows for pressure relief to occur which in turn helps to fully start the large nozzle assembly. At higher pressure ratios, as in series J, the increase in channel area apparently is not needed to get the nozzle to start as long as the incident wave does not reflect back into the nozzle.

Multi-Nozzle and Diffuser Array

The multiple nozzle array consists of three regions where the flow phenomena are studied. They include the nine nozzle passages, the constant area cavity, and the nine diffuser passages. Each of these areas have unique flow processes that occur during shock induced starting. In series G, H, I. L and M, the nozzles are fully started, but the diffusers are unstarted as was observed by Weber. The flow processes that are observed which lead to the nozzle starting agree with those Weber described in his work. Figure 13 shows the multi-nozzle array with only the nozzles started. The black streaks in the nozzle passages in that photograph are due to the oil that accumulated on the test section optical window in spite of every attempt to keep the shock tube free of oil.

In an effort to start the constant area cavity and the diffusers, several flow phenomena are observed. One phenomenon observed is the reflection of part of the incident shock wave off the leading edge of the diffuser vanes. In addition to the fact that the diffuser vanes presented a small frontal area for reflection, the fact that the flow is entering a converging channel helped generate these waves. These reflected waves are observed in series B, C, G and H. They are similar to the reflected waves that are observed when the incident shock wave encounters the nozzle faces. The waves start out as circular waves around the leading edges of the diffuser vanes and then expand and tend to coalesce into a single wavefront that propagates upstream. However, due to the complex nature of the flow in the cavity and the fact that the wave is moving opposite in direction to the flow of the medium, a uniform wavefront is never established. Figure 14 shows the life cycle of these waves from formation until they dissipate for the G-series. As they move

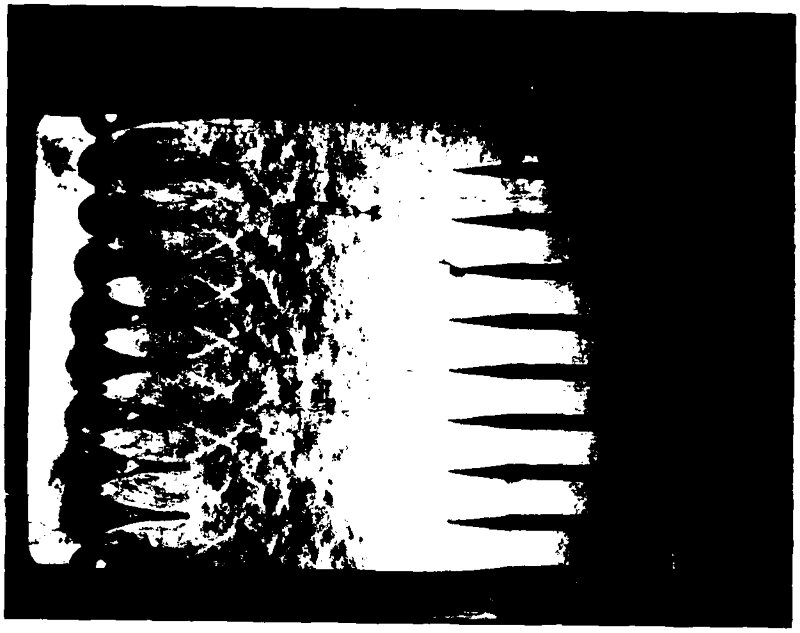


Fig 13. Multinozzle Array with Nozzles Fully Started

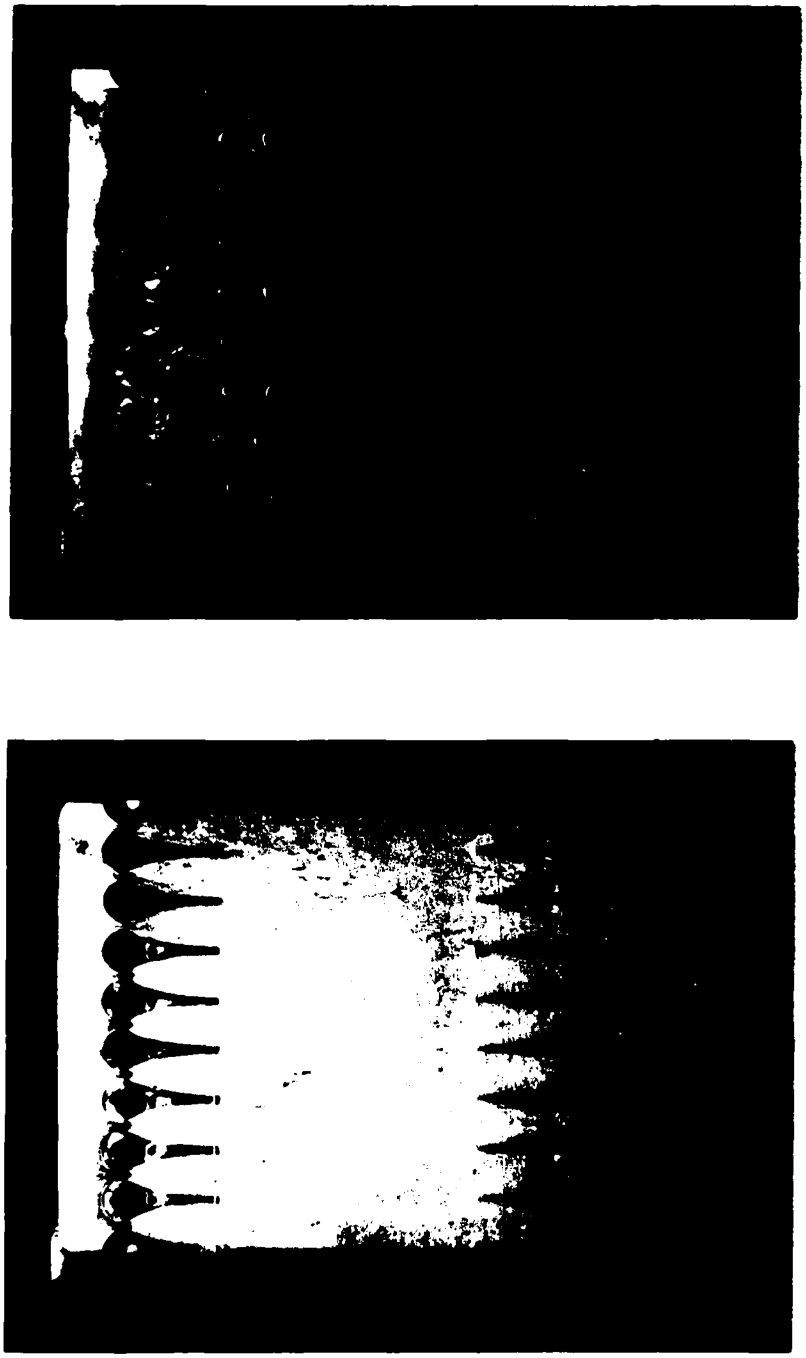


Fig 14. Life Cycle of Reflected Waves From Diffuser

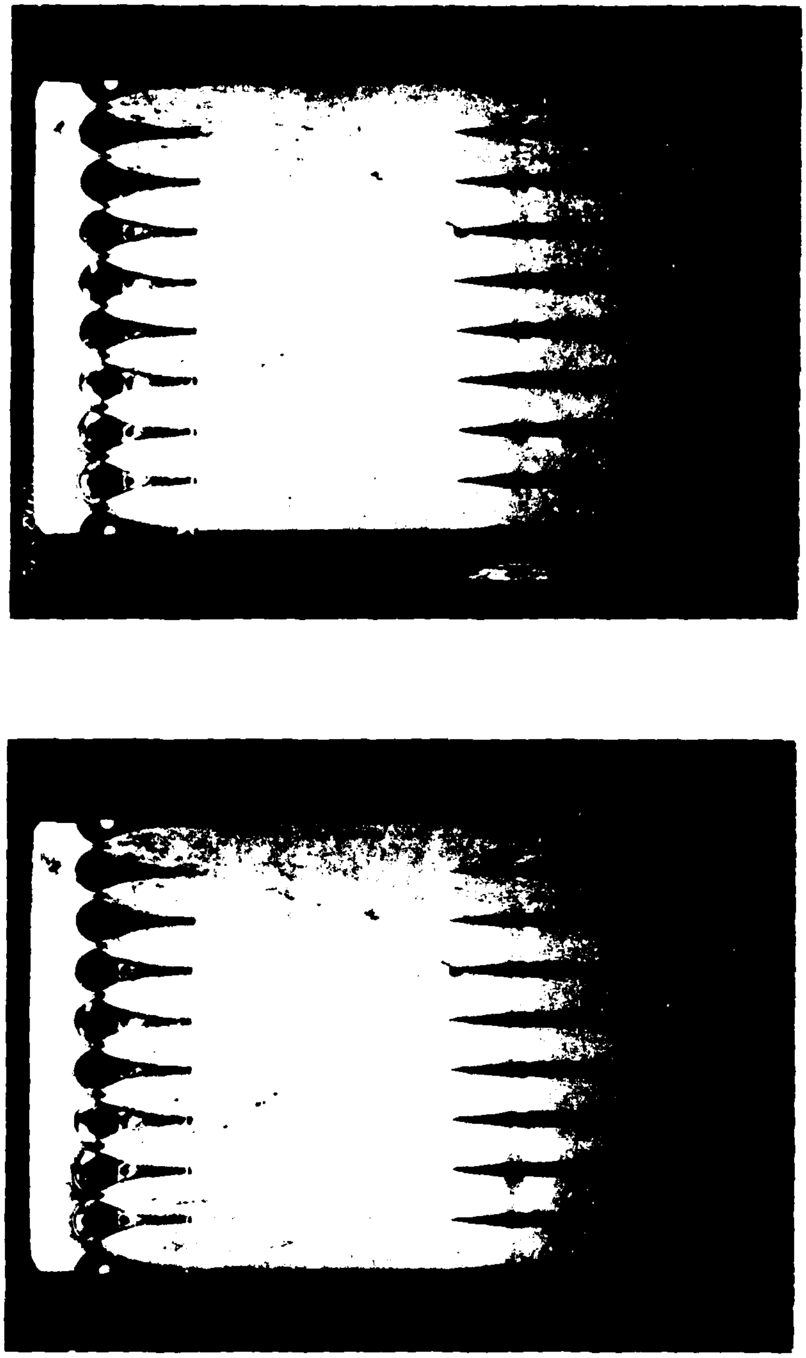


Fig 14. (Continued)

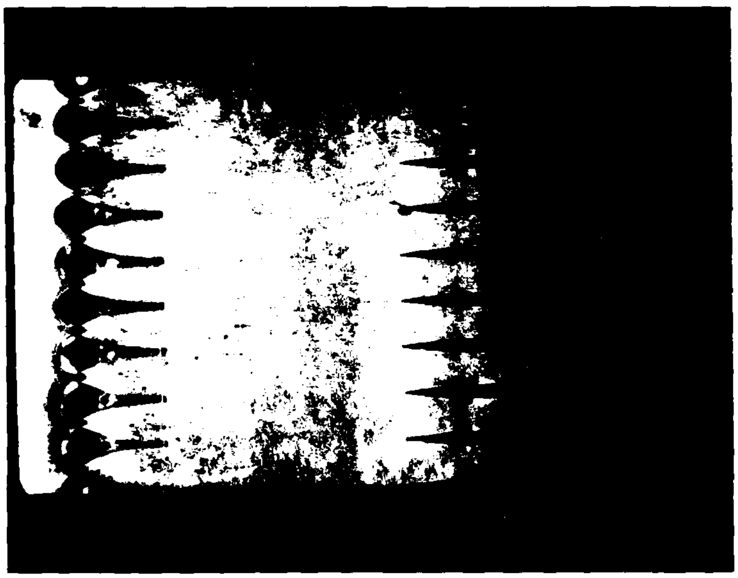


Fig 14. (Continued)

into the cavity behind the incident shock and downstream of the nozzle exit shocks, the flow conditions in this region cause the reflected wave to dissipate.

The conditions in the flow cavity are very complex and not fully understood. The reflected waves are believed to be weak because the area of reflection, the tips of the diffuser vanes, is small. This would indicate that the reflected waves are weaker than their counterparts from the nozzle entrance. An effect that appears to contribute to the weakening of these reflected waves is that since they start out small they must expand into the flow cavity. This increase in shock area results in a decrease in the shock strength.

The flow into which the waves reflected from the diffuser blades are propagating is highly transitory. The nozzles are fully started and the flow is supersonic in the nozzle and short distance into the cavity. Then a "normal shock region" occurs where the flow transitions to subsonic. This region appears to be more complex than a simple normal shock front and is highly dynamic. For most of the tests, the flow behind the incident shock wave is subsonic. However, in general, the flow speeds in the region downstream of the "normal shock region" and behind the incident shock waves are not believed to be the same. This leads to a highly dynamic and transitory flow in the cavity into which the reflected waves propagate. This complex flow region is believed to be responsible for the dissipation of the reflected waves.

Only four tests yielded conditions of fully started nozzles, diffusers, and cavity. The diaphragm pressure ratio for these tests is $P_{41} = 70$. Figure 15 shows the entire test section started. The classic mach diamond pattern is observed throughout the cavity and in the diffuser

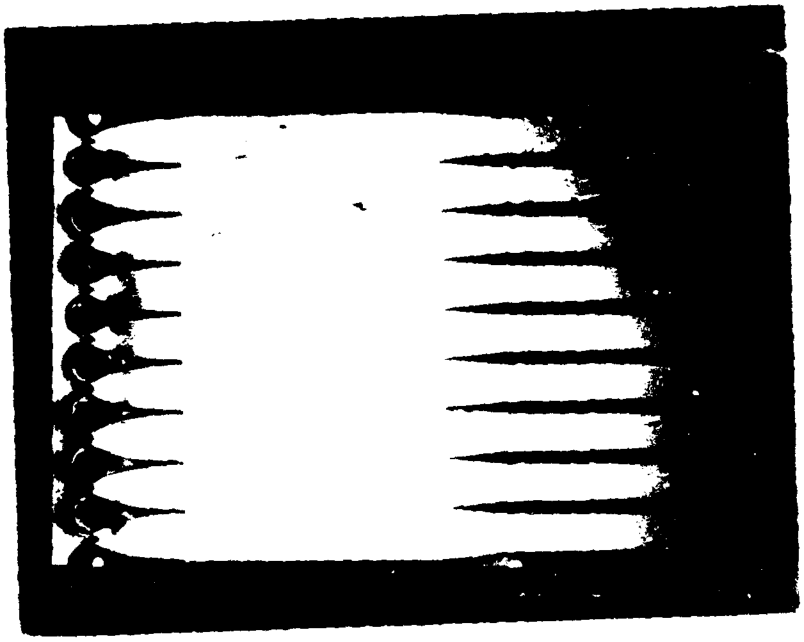


Fig 15. Multinozzle Assembly Fully Started

passages. However, other tests were made with this assembly in which the diaphragm pressure ratio was varied from 65 to 90 at intervals of 5; none of the other tests resulted in starting the cavity or diffuser. It is believed that the reason for this is due to the geometry of the test section. Since tests with the same flow conditions did not always start the assembly, it is conjectured that the diffuser is operating in the region where the area ratio is just above the minimum area ratio to allow starting under the test conditions in this study. Possibly the incorporation of a variable geometry diffuser would permit establishing the conditions for reliable starting of the nozzle-cavity-diffuser array and aid in investigation of the complex flow phenomena.

In summary, it can be seen that flow in GDL nozzle and diffuser passages is complex and highly dynamic during the starting of the assemblies. It was found that conditions in the test section depend not only on the flow quantities and test section geometry, but also in some cases on the flow channel geometry downstream of the test section. The processes that occur during shock induced starting are only beginning to be understood and more work is needed before the flow phenomena can be explained in detail.

IV. Conclusions

It is found that the shock induced starting of the supersonic nozzles and diffuser used in gasdynamic lasers is highly dynamic and transitory. It can be seen that for the right conditions both the large single nozzle and the multi-nozzle/diffuser array can achieve a fully started condition. The results in this work are in agreement with previous work done by others on these types of assemblies.

The starting of the large single nozzle in this study depends on the flow geometry and/or the initial conditions that establish the nozzle pressure ratio.

The conditions that allow the cavity and diffusers passages of the multi-nozzle assembly to become fully started are still not clearly understood at this time. Some of the flow phenomena behind the incident shock that are observed are explainable in terms of previous work and gasdynamic theory; however, due to the highly transient and dynamic nature of the flow, the exact conditions needed to fully start the entire array are not yet specifiable.

V. Recommendations

1. Further exploration into the conditions that yield a fully started nozzle-diffuser array are needed. It is recommended that some new flow geometry be explored. One flow channel should be a single small nozzle diffuser passage while another should be a multipassage array of perhaps four or five nozzles and diffusers. It would also be useful to explore a flow channel with a variable area diffuser. Combining these with more study of the current multi-nozzle test section could yield some useful insights into the starting conditions of these arrays. Work done on these assemblies would allow some of the unique flow phenomena that occur due to the geometry of the multi-nozzle arrays to be explored. It is believed that this would help explain why the multi-nozzle assembly only fully started in four test runs.

2. Another investigation that would prove very helpful would be to install pressure transducers along the sidewall of the large single nozzle. This would enable some quantitative measurements to be made of the flow.

3. It is recommended that before this study continue, a new spark lamp system be acquired. Due to the age of the current system, repair parts are unavailable and therefore the repair and reliability of the current is very much in question. With a new spark lamp system, the quality of the photographs could be greatly improved. Also helpful along this line would be a high speed motion picture camera that would be able to record an entire series of flow events. This would enable more detail to be recovered from the transients.

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Vita

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In this investigation, the flow processes involved in shock induced starting of nozzles and diffusers similar to those used in gasdynamic lasers were studied. Two geometrically similar nozzles were used. The throat opening in the large single nozzle was 0.276 inches. The other was an array of nine nozzle passages in which the throat opening was 0.069 inches. Downstream of the nine nozzles were nine diffusers whose minimum opening was 0.286 inches. These 2-dimensional nozzles and diffusers were 0.75 inches thick.

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The multiple nozzle and diffuser array is similar to those used in gasdynamic lasers. Schlieren photographs of the flow in these channels were the primary source of data for this investigation.

Afully started condition of uniform supersonic flow was achieved throughout the entire test area for both test sections. The processes leading to this condition were highly dynamic and complicated. It was found that successful starting depended not only on the initial diaphragm pressure ratio, but also the downstream test cell configuration. Starting the large single nozzle was enhanced by an increase of flow channel just downstream from the nozzle. This decreased the strenght of the incident shock wave and thereby increased the pressure ratio applied across the nozzle. As a result, the gasdynamic starting shock could pass on out of the nozzle at lower shock tube diaphragm pressure ratios than would have been the case if the area had remained constant in the flow channel behind the nozzle. The starting of the nozzle-diffuser array appears to depend on the flow area geometry in a non-linear manner.

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